Engineering Sustainability of Mechanical Recycling of Carbon Fiber Composite Materials

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ABSTRACT

The high demand for carbon composite in many industries results in an increase in the embodied energy footprint of carbon composites. Recycling technologies for carbon composites are being developed to reduce the embodied energy footprint of the material. The purpose of this research is to analyze and estimate the specific energy consumption from mechanical recycling method, specifically a ball mill with an air-classifier, which is not yet widely applied. The milling process is the most important step in recycling composites. The input energy requirement on milling process is calculated theoretically based on industrial scale (18ft x 22ft) over-flow ball mill based on different feeds and product sizes. It was assumed that the recycling process rate was 2100 ton/year. The specific energy for recycling carbon fiber reinforced plastic (CFRP) was significantly less than the embodied energy of virgin CFRP. Although the energy consumption depends on the method of recycling CFRPs, the difference in embodied energy between virgin CFRP and recycled CFRP can be very significant. The result shows that there can be environmental benefit from utilizing carbon waste with relatively low milling consumption in mechanical recycling. This research can provide further direction on how to model a closed loop of the overall composite recycling process.

Keywords
Carbon Fiber-reinforced plastics, mechanical recycling, ball mill, embodied energy, composite end-of-life alternatives

1. Introduction

Numerous industries, such as the aerospace and automotive, widely use carbon fiber reinforced plastics (CFRPs) for their application; as a result, the market demand for CFRPs has rapidly increased over recent years. The superior properties of carbon fiber and its composites such as high tensile strength, chemical and heat resistance, low thermal expansion and rigidity make the material ideal for aerospace and automotive use. The 2006 world capacity of CFRP composites was about 25,000 metric tons per year, and at that time was estimated to grow to 35,000 metric tons every year. The rapidly increasing rate on demand may cause a shortage to meet the new demand for carbon fiber. If the fibers are recycled and reused, this extends the lifetime of fibers and meets the future demand for carbon fiber which has an economic benefit. However, the noticeable lack of composite recycling is critical because this is a potential obstacle to the development and sustainable use of carbon fibers and other composite materials in the market. In this research, the purpose is to research and establish the basic steps of a closed-looped mechanical milling process for calculating embodied energy. Life Cycle Assessment (LCA) software is effective in evaluating the embodied energy over the complete recycling process; however, there are problems with the accuracy of information as the technique is still in fledgling stage. The main use of LCA is to provide a comparison between the use of different materials or manufacturing processes for a given product to determine the benefits or disadvantages of adopting a specific design strategy. It is, however, very difficult to assess the impact of a single product without a comparison since the impact value cannot be analyzed as an absolute value. Therefore, since most of the LCAs software do not have relevant data for composite materials, the appropriate equations are necessary for calculating the embodied energy.

1.1 Composite recycling methods

Carbon fibers can be recycled via three different energy approaches: thermal, chemical, and mechanical recycling. In thermal recycling, the matrix is separated from the fibers using heat to decompose the scrap material. The three types of thermal recycling are combustion, fluidize-bed combustion, and pyrolysis. The combustion process is useful to separate the short fibers or particles from the resin part of composite [1]. The overall cost can be saved since heat is the major cost in this process. However, a large amount of ash is required to be disposed by landfilling, which can potentially increase the environmental concerns. The fluidized-bed combustion has received great attention from the industry experts. This method works at elevated temperatures to decompose the scrap composite in a silica sand bed that is heated by hot air [12]. This process provides the relatively well recovered fiber with little surface damage. However, the main obstacle is that this process reduces the size of composites before the thermal treatment. In pyrolysis, the matrix phase is used for energy to self-sustain the process in addition to the fiber recovery [4]. However, the recovery of composite is very dependent on temperature. In chemical recycling, the matrix is separated from the fibers in a chemical reaction, which is called super-critical fluid [5]. Among various recycling technologies in industries, the most matured technique is mechanical recycling. The mechanical recycling process is focused on the milling and grinding processes. After suitable size reduction, the material is ground in a hammer mill and graded into different fraction [1]. However, this approach was challenged economically before ball milling process combined with an air classifier was adopted; since it is hard to produce finely ground recyclates at a low cost when compared to the other processes [3]. As the milling process is technologically advanced, the mechanical process is becoming best possibility to process the composite waste.

1.2 Embodied energy of virgin composite and recycled composite

In order to understand economic and environmental benefits, the embodied energy of each material during the entire life cycle must be compared. The analysis of embodied energy provides the total energy inputs consumed by the material from birth to production life cycle phases. Fig 1 shows the embodied energy of different major engineering materials. The virgin carbon fiber has the highest embodied energy because the manufacturing process for carbon fiber requires high temperature during carbonization. In addition, two other major processing steps for carbon that requires massive energy consumption are oxidization and stabilization.

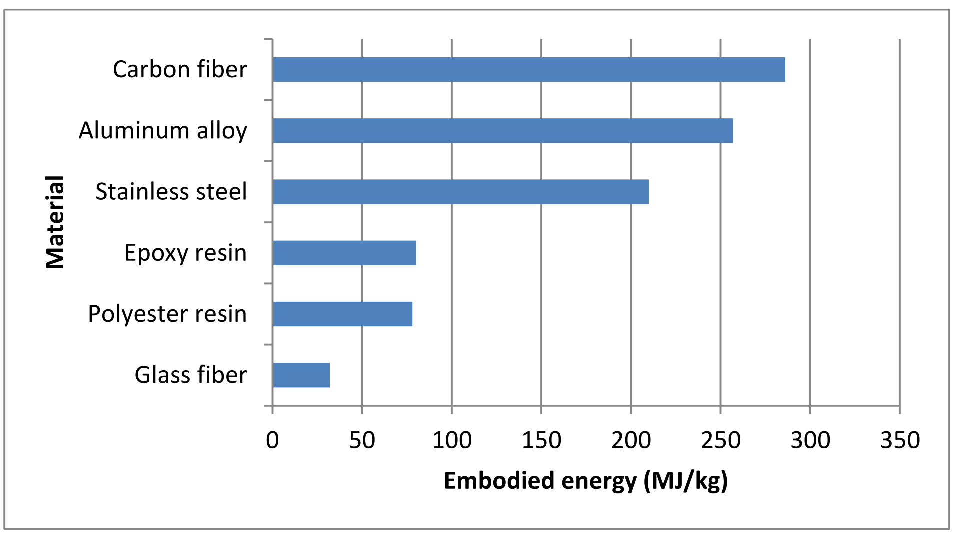

Fig. 1 Embodied energies of common composite constituent materials and 2 common metals [2]

The embodied energy for carbon fiber can be significantly reduced by recycling required carbon fibers. Table 1 provides the energy intensity (MJ/kg) of virgin and recycled materials for the automotive industry. The virgin carbon fiber reinforced thermoplastic (CFRTP) requires 155MJ/kg to manufacture the automotive body while the recycled CFRTP consumes 15MJ/kg. The majority of energy consumption occurs during the carbon fiber production. Thus, there is great motivation for recycling the carbon fiber.

Table 1. Energy intensity (MJ/kg) of virgin and recycled materials [11]

	Steel	Virgin CFRTS	Recycled CFRTS	Virgin CFRTP	Recycled CFRTP
Assembly molding	16	13	10	10	10
Steel or matrix resin production	33	23	13	13	
Carbon fiber production		198		132	
Material recovery			10		5
Total energy intensity (MJ/kg)	49	234	33	155	15

CFRTP: carbon fiber reinforced thermoplastic; CFRTS: carbon fiber reinforced thermoset

2. Research Methodology

A specific energy equation is used to design a mathematical model that can be validated for industrial composite recycling using mechanical ball milling. The electrical energy requirement for the mechanical recycling process is modelled using the energy demand model [6], as shown in Equation (1)

$$\mathrm{E} = (P_c + P_d)t \qquad (1)$$

where E is the energy required, P_c is the comminution power (CP) in Watts consumed by ball milling machine, P_d is the mill power draw for running at no load, and t is the total machining time in sec. The CP requirement can be specified [13] as shown in Equation (2).

$$P_c = \mathrm{W} \times \mathrm{BCEF} \times \mathrm{FGF} \times \mathrm{FMD} \times \mathrm{RREF} \times \mathrm{SSF} \times \mathrm{MT} \times \mathrm{EF1} \times \mathrm{EF2} \times \mathrm{EF3} \qquad (2)$$

Where:

W = Basic power required

BCEF = Ball charge efficiency factor = $\left(\frac{V}{0.4}\right)^{0.333}$

FGF= Fine grinding factor = $\frac{P+10.3}{1.145*P}$ $for\ P < 75\ microns$

FMD = Mill diameter factor for mill diameter = $\left(\frac{8}{D}\right)^{0.2}$

RREF = Reduction ratio efficiency factor = $\left(\frac{(20 \times (Rr-1.35)+2.60}{20 \times (Rr-1.35)}\right)$ *Rr = $\frac{F}{P}$

SSF = Shell speed factor for shell speed = $\left(2-\frac{2.8}{S}\right)^{Z}$ *Z= $-\left(\frac{D}{17.08}\right)^{3}$

MT = Mill type (Based on Ball = 1)

EF1 = Wet or Dry (Based on Wet = 1)

EF2 = Circuit Type (Based on Open = 1)

EF3 = Diameter Efficiency (0.91)

The basic energy, W, is calculated by the empirical Bond equation which expresses the correlation between material toughness and power required in the comminution machine [15]. The work done in reducing a mass of material from representative size ${d_{80}}^{F}$ to representative size ${d_{80}}^{P}$ is given by the bond Equation (3)

$$\mathrm{W}= \mathrm{K}\left(\frac{1}{\left({d_{80}}^{P}\right)^{1/2}} - \frac{1}{\left({d_{80}}^{F}\right)^{1/2}}\right) \mathrm{kWhr/ton} \qquad (3)$$

P= Product size (mm)   F= Feed Size (mm)

The relationship between feed 80% passing size in microns, ${d_{80}}^{F}$ and product 80% passing sizes in microns, ${d_{80}}^{P}$is the hypothetical reduction of 1 ton of material from a very large size to a representative size of 100microns [15]. This energy is called the work index of the material WI.

$$\mathrm{WI} = \ \mathrm{K}\left(\frac{1}{(100)^{1/2}} - \ 0\right) \mathrm{kWhr/ton} \rightarrow \mathrm{K} = 10\mathrm{WI}$$

$$W\ = 10\mathrm{WI}\left(\frac{1}{\left({d_{80}}^{P}\right)^{1/2}} - \ \frac{1}{\left({d_{80}}^{F}\right)^{1/2}}\right) \mathrm{kWhr/ton} \qquad (4)$$

The representative size is conventionally taken as an 80% passing size. WI is usually different depending on the milling method. The standard WI value was designed to produce an index that would correctly predict the power required by a wet overflow discharge ball mill. The mill power draw P_d can be estimated by the actual operation data.

3. Evaluation Procedure

Evaluation of the embodied energy requirement in mechanical recycling of CFRP was calculated by using a Metso Overflow Ball Mill which is size of 18ft × 22ft that operates in closed circuit with a classifier at a 250% circulating load. The type of ball inside of the mill is made of cast iron. The data samples were calculated on a CFRP which has a fiber volume fraction of 55% provided by the Recycled Carbon Fiber Ltd. The milling conditions used are listed in Table 2.

Table 2 Mechanical recycling of ball milling condition

Wet or Dry	Wet
Circuit	Closed
Mill diameter (ft)	18
Mill length (ft)	22
RPM (rev/min)	13
Feed 80% passing size (mm)	5,10,15,20,25
Product 80% passing sizes (mm)	0.045

The amount of carbon fiber recycling was estimated as 2000 tons per year based on a limited capacity to process. The assumed feed passing size varied from 5mm to 25mm. The work index, WI used was 14kWh/t for the CFRP according to the Typical Bond Index value. For each test, the power draw is determined by the calculation software designed by the Smart Dog Mining Company who developed the software from information gathered over 40 years in the mining industry. Thin composite panels are fed into the machine through the chute and mechanically reduced by milling until short fiber and resin powder can be sieved though the air classifier. The short fibers can then be used as fillers in re-manufacturing. If the thicker panel has to be processed, it is required for crushing in small sizes using a jaw crusher. The CFRP plates of 25mm thickness were used before passing the mill and the desired size after passing the mill was 0.045mm of thickness.

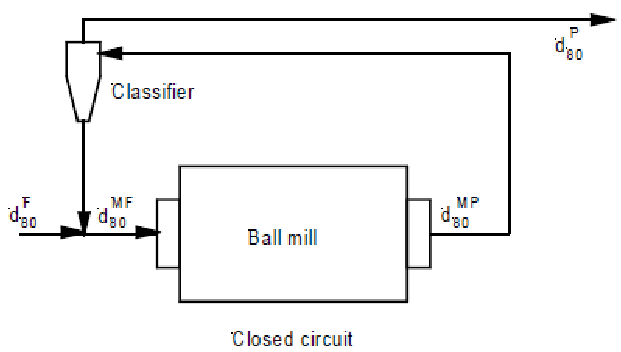

Figure 2. Application of Bond work index for calculating power required for closed milling circuit [9]

4. Result and discussions

Figure 3 shows the results obtained from the ball mill recycling of CFRP at each different size of samples, and presents how much power is demanded as the feed size increases. The total power increases as the feed size is enlarged. However, the power requirement became stable at some point. The curve has an opposite relationship between power demand and product size. As the product size decreases, the power demand increases. This is called size effect in machining. At the lowest feed size, a significant increase in specific energy is experienced and at this level, material ploughing is expected to dominate.

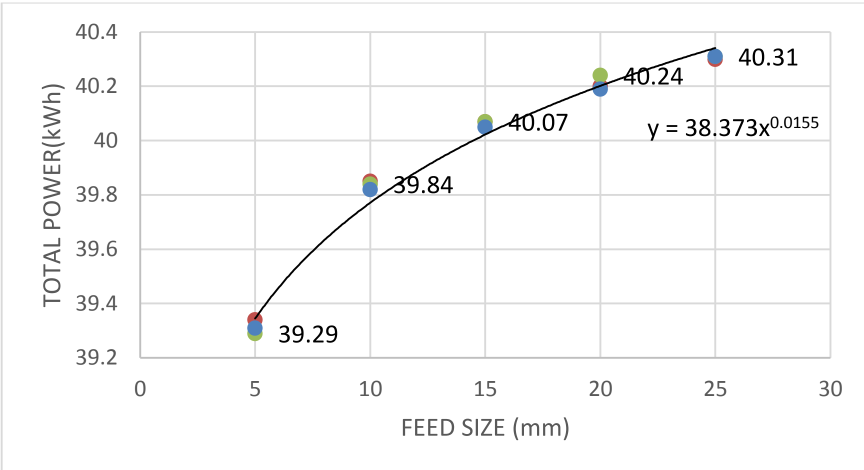

Figure 3. Relationship between power demand and feed size

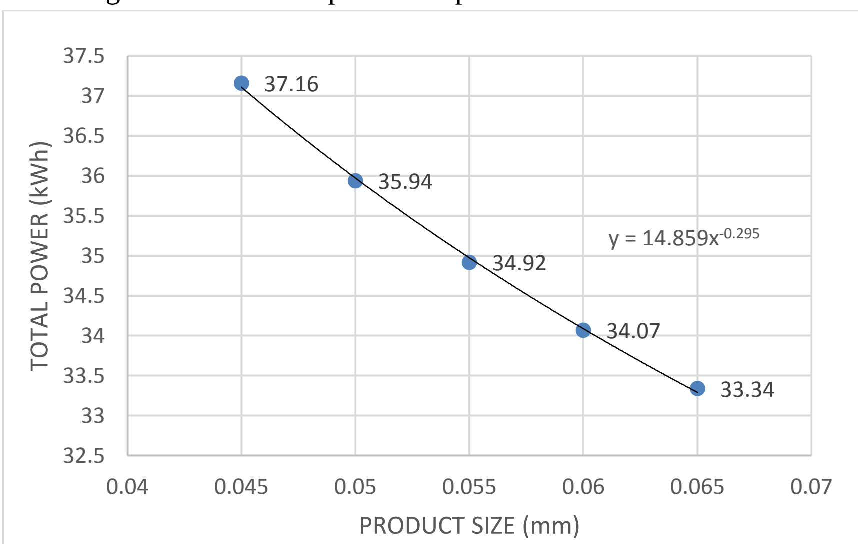

Figure 4. Relationship between power demand and product size

For the Metso overflow ball mill machine, the basic power was estimated using the Smart Dog Mining calculation software, and the sample data was obtained from Recycled Carbon Fiber Ltd. The power draw is calculated as approximately 23kWh for all samples and the total power for the power draw and basic comminution power values ranges from 39kWh to 40.3kWh. The process energy is found to be 0.57 MJ/kg based on size reduction by industrial ball milling. This is based on 55% volume fraction of fibers and a CFRP density of 1.5g$/cm^3$. The specific energy is increased to 0.57, 0.58, 0.58, 0.59 and 0.59 MJ/kg as feed size is increased to 5, 10, 15, 20, and 25mm respectively. The total power is stabilized to converge at a certain end point as shown in Fig. 4. These values are significantly lower when compared with the embodied energy of virgin CFRP (234MJ/kg), which means mechanical recycling using ball mill can reduce the specific energy consumption significantly. As a result, using a closed-loop recycling solution can be valuable for a variety of industries in order to recycle composites mechanically.

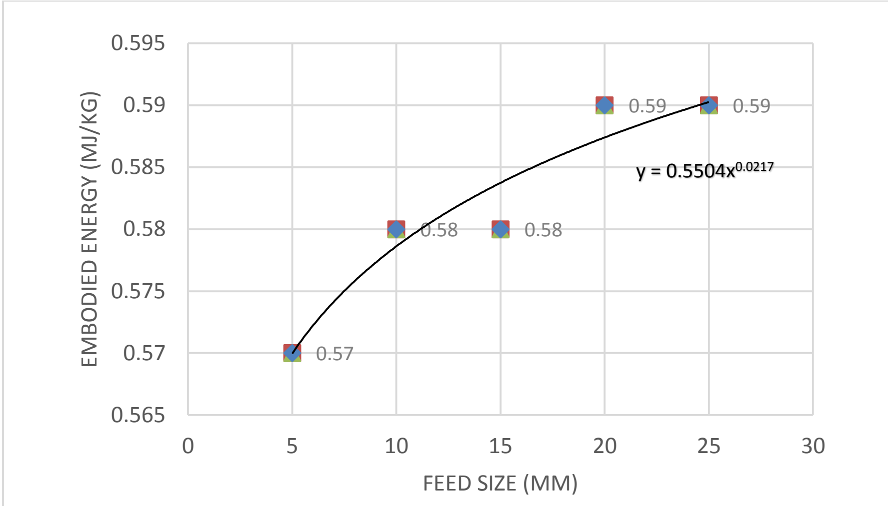

Figure 5 Mechanical CFRP recycling process energy by industrial ball mill

5. Conclusion

The goal of this research was to model energy demand in mechanical recycling. The approach was based on the mechanics of machining where mathematical models involving specific energy equations was required to predict energy demand in ball milling. This approach gave future considerations for processing conditions in defining the resource foot print. The total energy demand from the power draw and comminution power in ball milling processing was 39kWh at the first run time and increased up to 40.31kWh. This gave an upper unit process energy value of 0.57MJ/kg based on size reduction by industrial ball milling. This result illustrates that the ball milling processing is much more energy efficient compared with other processing methods such as chemical and thermal recycling. The unit energy for composite manufacturing processing is higher than that of ball milling recycling and this recycling method is significantly lower than the embodied energy of virgin fibers (234MJ/kg). Specifically, the ball milling method can be environmentally beneficial because there are no chemical catalysts or substances used. Further work on the research project should be focused on developing a closed-loop that will include all other stages of manufacturing of carbon fiber, in order to estimate more comprehensive specific energy consumption.

6. Acknowledgements

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